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ADVANCED PHOTOSENSORS FOR LASER BEACON ADAPTIVE OPTICS ON THE STARFIRE OPTICAL RANGE 3.5 M TELESCOPE: PREPRINT

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Technical Paper

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14. ABSTRACT

Total upgrade of 3.5 m sodium guidestar adaptive optics for space situational awareness (NGAS). 24x24 subaperture AO system in compact coude path. High optical throughput; efficient use of sodium beacon and other signals. Using existing 50w sodium laser. Replace all optics except for primary. Replace all sensors.

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Advanced photosensors for laser beacon adaptive optics on the Starfire Optical Range 3.5 m telescope

Advanced Maui Optical and Space Surveillance Technologies Conference

Robert Johnson, Ph.D.
Directed Energy Directorate,
Air Force Research Laboratory

THE AIR FORCE RESEARCH LABORATORY
LEAD I DISCOVER I DEVELOP I DELIVER

Outline

- Background & status
- Motivation
- Status of CCID-66
- Shared MIT Lincoln CCD lot with TMT and Keck
- APD arrays
- Summary

photo by R. Fugate, 4 sec exp, f/2.2, f=35 mm

Total Upgrade of 3.5 m

Sodium Guidestar Adaptive Optics for
Space Situational Awareness (NGAS)

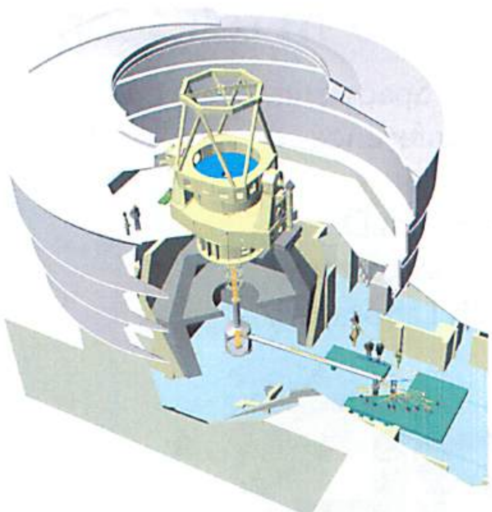


image by J. Spinhirne and B. Agena

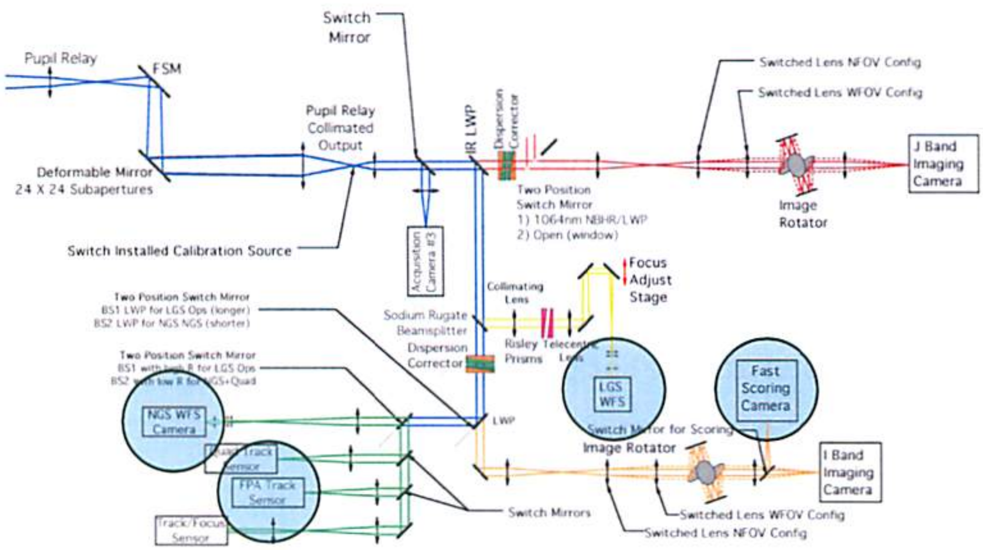
- 24×24 subaperture AO system in compact coudé path
- High optical throughput: efficient use of sodium beacon & other signals
- Use existing 50 W sodium laser
- Replace all optics except for primary
- Replace all sensors

3.5 m AO Upgrade Status

- Primary removed; plan to recoat mid-Sept.
- Coudé lab gutted; optics benches installed
- Optics: large fraction delivered; mounts in fabrication
- New fast steering mirror and deformable mirror delivered
- CCID-66 complete; electronics in work
- APD arrays: 16×16 subaperture 2nd prototype delivered

Sensors for 3.5 m AO Upgrade

drawing by J. Spinhirne



Arrays for Wavefront Sensing

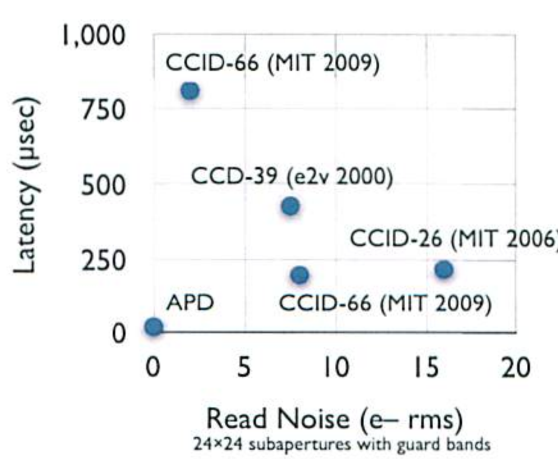
Better AO performance with low read noise and low latency

Avalanche photodiode arrays

- Geiger mode, *no read noise*, direct to digital, fast readout
- Drawbacks
  - Crosstalk
  - Probability of detection ~0.5

Approach

- Continue CCD development while working on issues with APD arrays
- CCID-66, 2-stage JFET amplifier



CCID-66 Description

- 160×160 pixels, 21 μm square
- 16×80 pixels per channel with frame store
- 20 channels, 3–10 MHz per channel, > 3000 fps
- 2-stage planar JFET, low cap, high responsivity
- Proven 1.3 e^- at 0.5 MHz single-stage planar JFET
- Estimate 8 e^- at 5 MHz two-stage planar JFET
- QE 0.8 at 589 nm

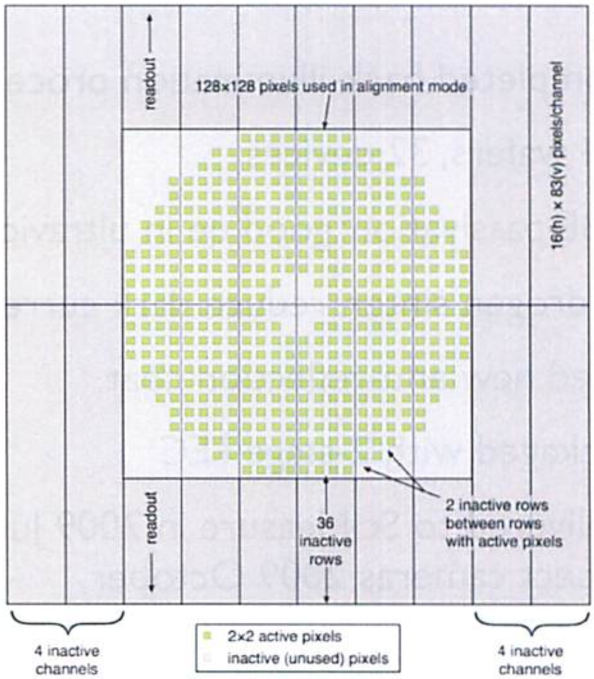
WFS Requirements

Estimates for CCID-66 with a 5 MHz pixel clock

Description	Units	Threshold	Goal	Estimate
Subaperture number (WFS)	—	24×24	24×24	40×40
Integration time (WFS)	ms	0.25	0.1	0.2
Frame rate (WFS)	fps	4000	10000	4000
Quantum efficiency (WFS)	—	0.45	0.45	0.8
Read noise	e^-	8	—	6
Dark counts	e^-/ms	10	—	10
Crosstalk	%	< 5	< 3	1
Read-out latency	μs	90	15	200

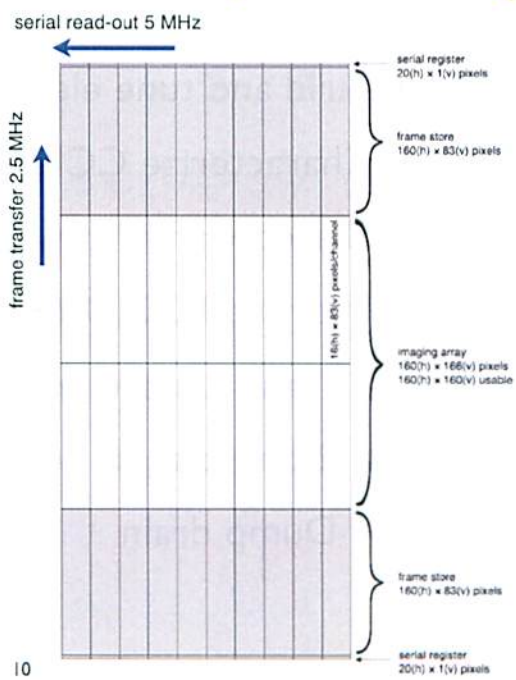
Requirements are similar for APD WFS. CCD-66 also used for Scoring and FPA Tracker.

24×24 Shack-Hartmann WFS



CCID-66 Latency

- Integrate
- Transfer 83 rows to frame store
- Transfer 37 unused rows to serial register and dump
- Transfer and read out 2 rows
- Transfer and dump 2 rows
- Repeat 11 times
- Latency > 180 μs
  $166 \times 0.4\mu s + (24+11) \times 16 \times 0.2\mu s$



CCID-66 Progress

- Completed back-illumination processing
  - 4 wafers, 32 devices
- MBE passivation: good qe in ultraviolet
- Hydrogen sinter: reduce dark current
- Used new anti-reflection coat
- Packaged with 2-stage TEC
- Delivered to SciMeasure in 2009 July, expect cameras 2009 October

Planned CCD Work

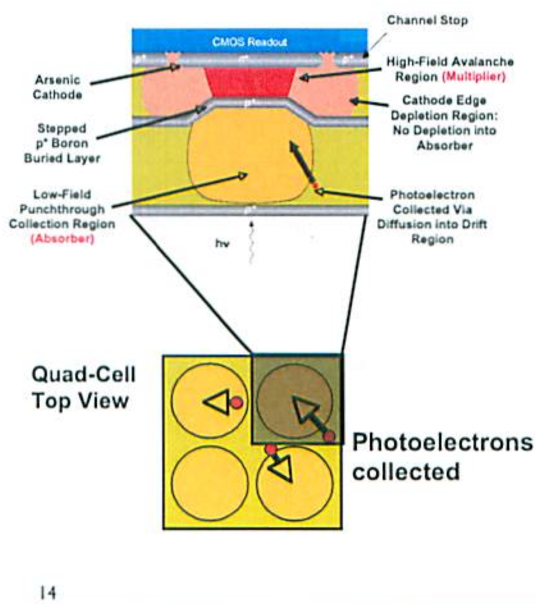
- Build and tune electronics (SciMeasure)
- Characterize CCID-66 at SOR
- Shared wafer lot with TMT+Keck
- Improved CCID-66
  - 1 and 2 stage amplifiers
  - 2 phase serial register
  - Dump drain

Shared Wafer Lot

- 160 x 160 pixel adaptive optics (AO) imagers
- 256 x 256 pixel AO imagers
- 1k x 1k imagers
- Polar Coordinate Detector Prototype
- 12 wafer lot
  - split into 3 different implant levels for the planar JFET
  - 4 wafers per split

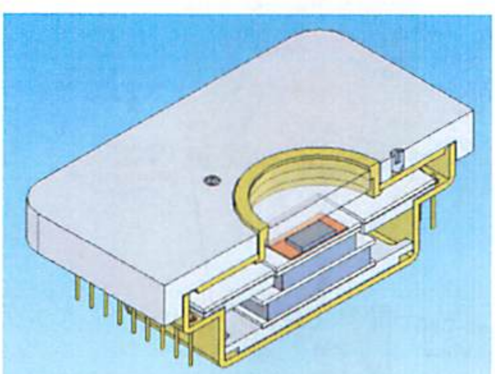
APD Design Details

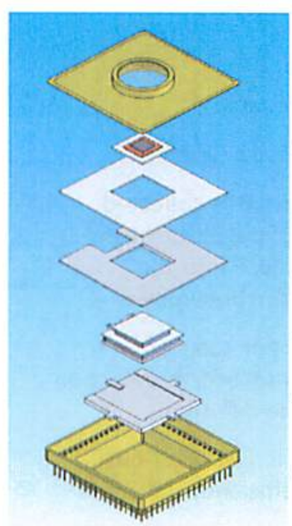
- High Fill Factor
- Geiger Mode Operation
- Photoelectrons collected outside of punch-through region diffuse into the cathode for breakdown
- With proper tuning of p+ doping, mostly drift detection with some diffusion
- Photons in center of quad-cell are efficiently collected



APD Array Prototype

APD Array Package





Lid

Sensor

Interposer board

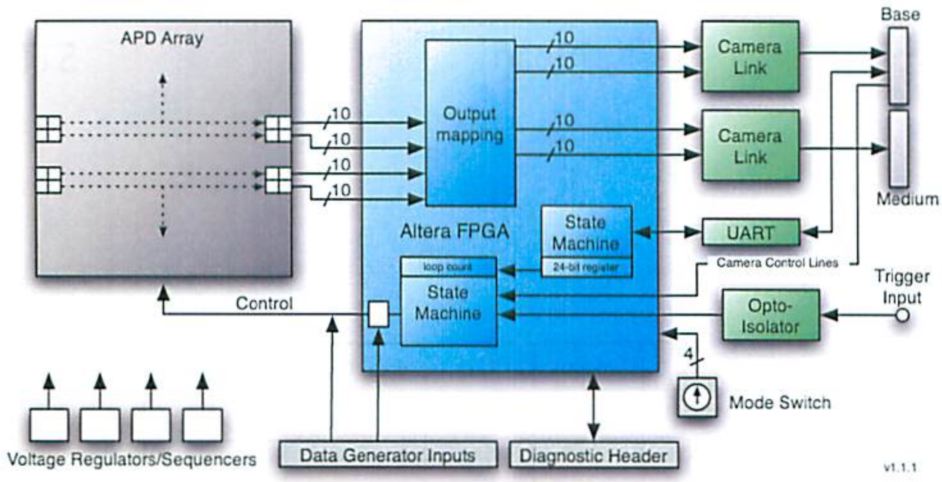
Interposer spacer

TEC

TEC spacer

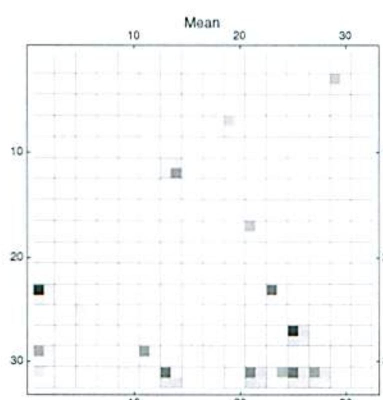
Case

APD Electronics

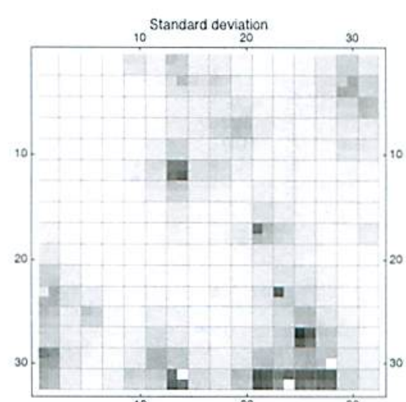


16×16 Prototype Tests

Dark frames (0.5 ms integration)



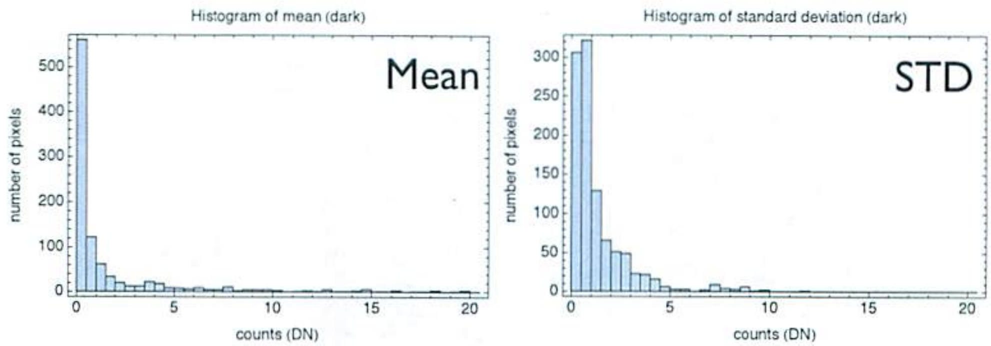
Mean = 2.7 counts



STD = 2.3 counts

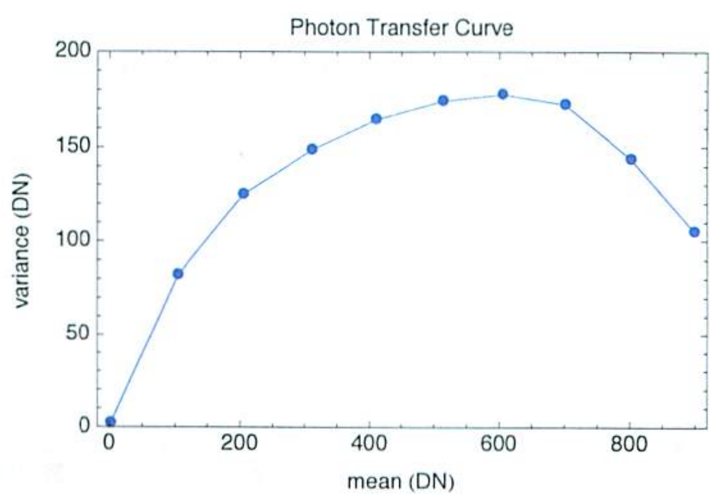
16×16 Prototype Tests

Histograms of Dark Counts (0.5 ms int.)



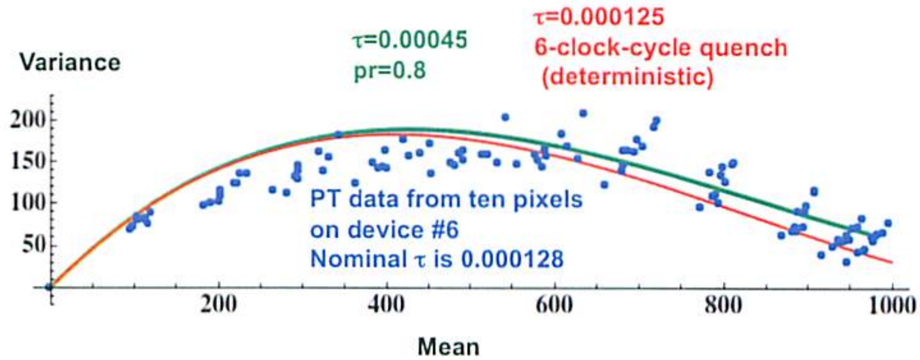
0.5 ms	Mean	STD	Mean Good	STD Good
Mean	10.3	62.0	2.7	2.3
STD	1.3	1.5	—	—

16×16 Prototype Tests



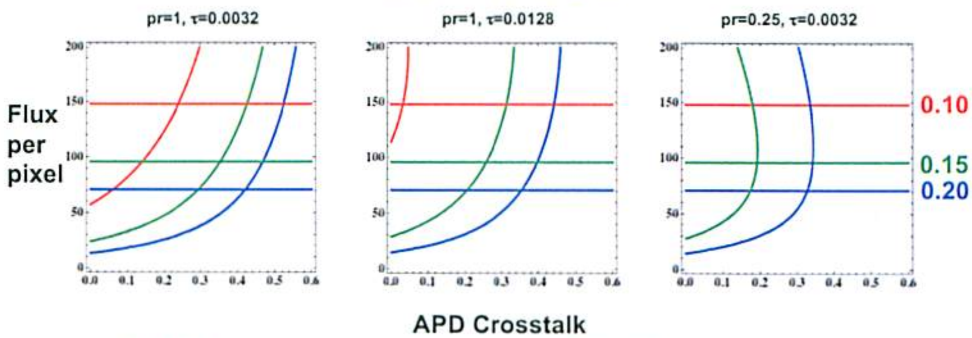
Read noise 0.6 e⁻, Gain 1.29 e⁻/DN
Should be read noise 0 e⁻, gain 1.0 e⁻/DN; finer sampling at low flux should show this.

APD Model vs. Data



results courtesy of B. Aull

Centroiding Accuracy Contours: APD vs. CCD



- CCD (horizontal lines) has unity QE, 27 e- readout noise
- APD (curves) has 50% PDE and varying crosstalk
- Middle graph has 4x longer clock period than left graph, right graph has 4x stochastic prolongation of quench time
- Stochastic quench prolongation produces noisy resetting at high fluxes, degrading performance much more than with just the extra signal blockage

results courtesy of B. Aull

APD Array Status

- BBAPD Lot 2 Complete
  - 16×16 & 32×32 quad-cells, test structures
  - Tests show high peak field causes tunneling current, initiates linear-mode avalanche near edge of device
  - Other wafers will get P implant to reduce field at edge
- SOR2008 ROIC complete
  - Included Tyrell arbiter circuits (resolve crosstalk)
  - Improved reset circuit (< 224 ns)
  - Modified PCB for extra bias voltages

Summary

- Expect CCID-66 camera delivery late 2009
- Shared CCD lot 2010
- Continue APD development

Backup

New 3.5 m Coudé Room

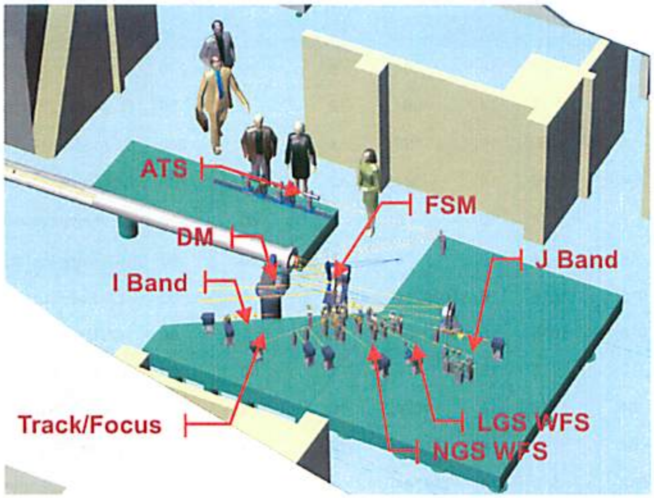


image by J. Spinhirne and B. Agena

- Turbulence simulator
  - In-lab check-out
- DM & FSM not at pupil
  - Compact design
- LGS + NGS capability

New Sensors for 3.5 m

Name	Make	Sensor (array size)	Model	λ (nm)
LGS WFS	MIT/LL	Si APD 32×32 subapertures	APD32	589 ±15
LGS WFS Interim	MIT/LL	Si CCD JFET 160×160 pixels	CCID-66	589 ±15
NGS WFS	MIT/LL	Si APD 32×32 subapertures	APD32	480 – 640
NGS WFS Interim	MIT/LL	Si CCD JFET 160×160 pixels	CCID-66	480 – 640
Tilt+Focus	MIT/LL	Si APD 32×32 subapertures	APD32	480 – 640
Tilt+Focus Interim	MIT/LL	Si APD 16×16 subapertures	APD16	480 – 640
I-Band Imager	MIT/LL	Si 1024×1024 pixels	—	650 – 1000
J-Band Imager	Teledyne	InGaAs 1020×1020 pixels	Hawaii-1RG	1100 – 1350
NGS Tracker	TBD	TBD quad cell	TBD	480 – 640
Scoring Sensor	MIT/LL	Si CCD JFET 160×160 pixels	CCID-66	650 – 1000
Correlation Tracker	MIT/LL	Si CCD JFET 160×160 pixels	CCID-66	480 – 640
Acquisition (×3)	Q-Imaging	Si EMCCD 512×512	e2v CCD97	480 – 1000

Formats of Sensor Data

Camera Name (unofficial)	Sensor array size	Pixels vert per channel (read out)	Pixels horiz per channel (read out)	Bits	Pixels per channel	Chans	Pixel rate per channel (M pix/s)	Total pixel rate (Mpix/s)	Interface (words x bits)
LGS WFS	32×32 subaps	6	32	10	192	4	60	240	CL Medium (4×10)
LGS WFS Interim	160×160 pixels	24	16	14	384	12	3	36	CL Medium (2×16)
NGS WFS	32×32 subaps	6	32	10	192	4	60	240	CL Medium (4×10)
NGS WFS Interim	160×160 pixels	24	16	14	384	12	3	36	CL Medium (2×16)
Tilt+Focus	32×32 subaps	2	4	10	8	2	60	120	CL Medium (4×10)
Tilt+Focus Interim	16×16 subaps	4	4	10	16	1	60	60	CL Base (2×10)
I-Band Imager	1024×1024 pixels	1016	1016	16	1032256	16	5	80	CL Base (1×16)
J-Band Imager	1020×1020 pixels	1016	1016	16	1032256	16	5	80	CL Base (1×16)
NGS Tracker	16×16 subaps	2	2	10	4	1	60	60	CL Base (2×10)
Scoring Sensor	160×160 pixels	64	16	14	1024	16	3	48	CL Medium (2×16)
Correlation Track	160×160 pixels	64	16	14	1024	16	3	48	CL Medium (2×16)
Acquisition (×3)	512×512 pixels	512	512	14	262144	1	5	5	Firewire (IEEE1394)

gray = SOR Fabric interface

Types of Sensors

Sensor	Pixels (total)	Pixel Size (µm)	Function
MIT Lincoln APD16	32×32	50	NGS Tracker Tilt+Focus Interim
MIT Lincoln APD32	64×64	50	LGS WFS, NGS WFS Tilt+Focus
MIT Lincoln CCID-66	160×160	21	Scoring Sensor, FPA Tracker LGS WFS Interim, NGS WFS Interim
Teledyne Hawaii-1RG	1000×1000	18	J-Band Imager
MIT Lincoln 1k×1k	1000×1000	13	I-Band Imager
e2v CCD97	512×512	16	Acquisition

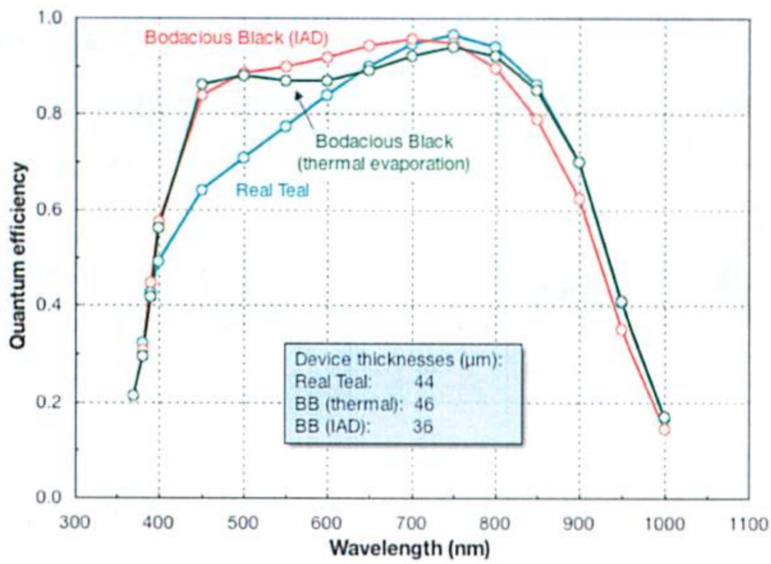
discussed in this talk

Selected Requirements

threshold [goal]

Sensor	λ (µm)	read noise (e^-)	dark count (e^-/ms/pix)	frame rate (10^3/s)	crosstalk (%)	latency (µs)
LGS WFS	0.589±0.015	0 [0]	0.5 [0.5]	4 [10]	5 [3]	90 [15]
Interim NGS WFS	0.48 – 0.64	8 [8] (at 5 MHz)	10 [10]	4 [10]	5 [3]	90 [15]
Tilt+Focus	0.48 – 0.64	0 [0]	0.5 [0.5]	2 [4]	5 [3]	90 [15]
I-Band	0.65 – 1.0	20	10 [1]	0.004	3 [1]	—

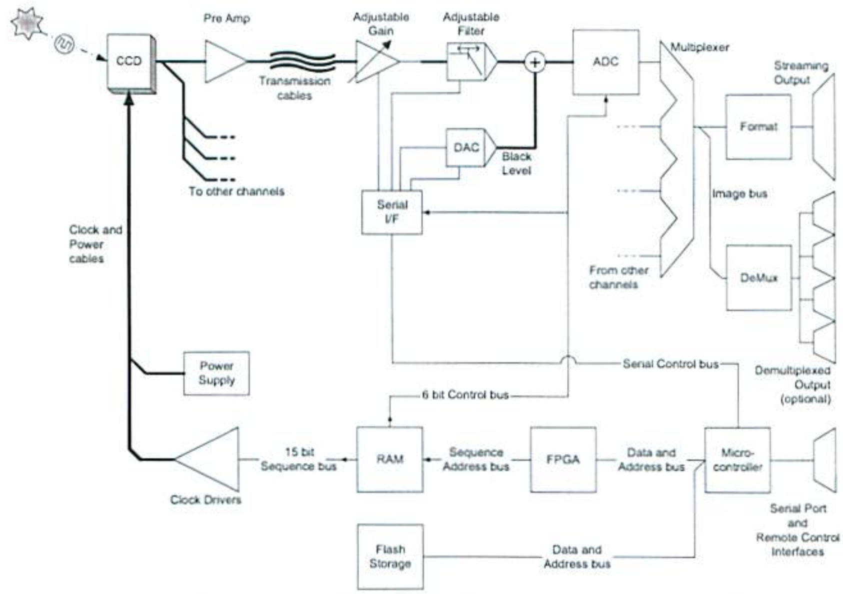
CCID-66 AR Coating



Mira Design Details

- InGaAs diode array
- Indium bump-bonds to ROIC
- Each pixel has an amplifier
- Voltage signals output to a multiplexer
- 16 channels in parallel, 16-bit digitizer
- Read-out takes approx. 0.7 sec
- No anti-blooming, no guide window

CCD Electronics



SciMeasure electronics: functions divided into modules

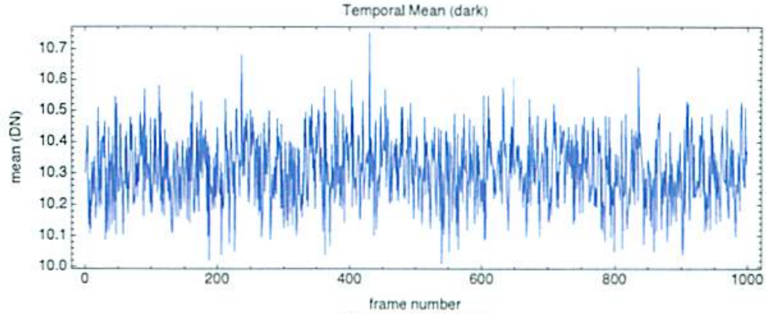
CCD Electronics

courtesy of R. Dueck

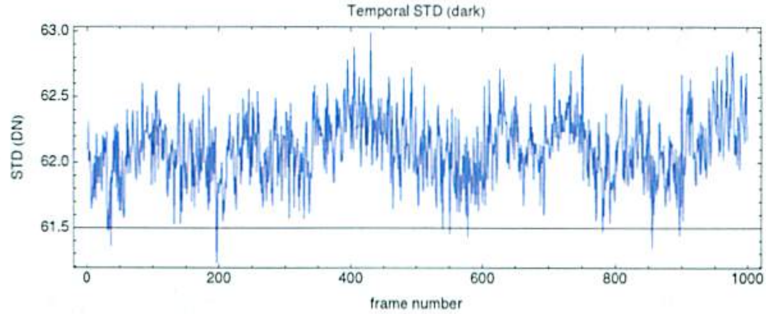
SciMeasure electronics and camera head for CCID-26

16×16 APD Prototype Tests

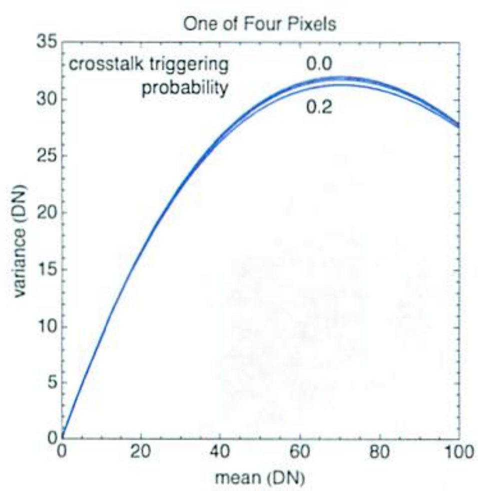
Mean

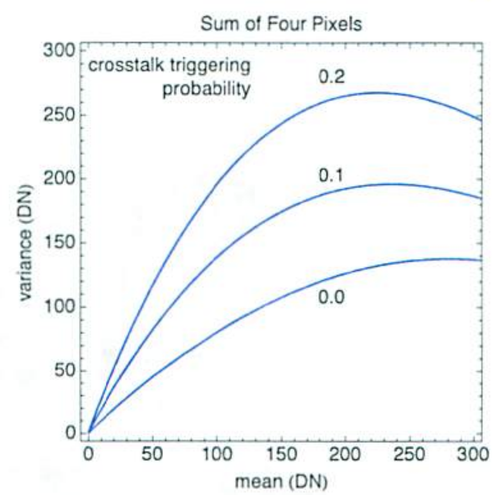


STD



APD Model Results

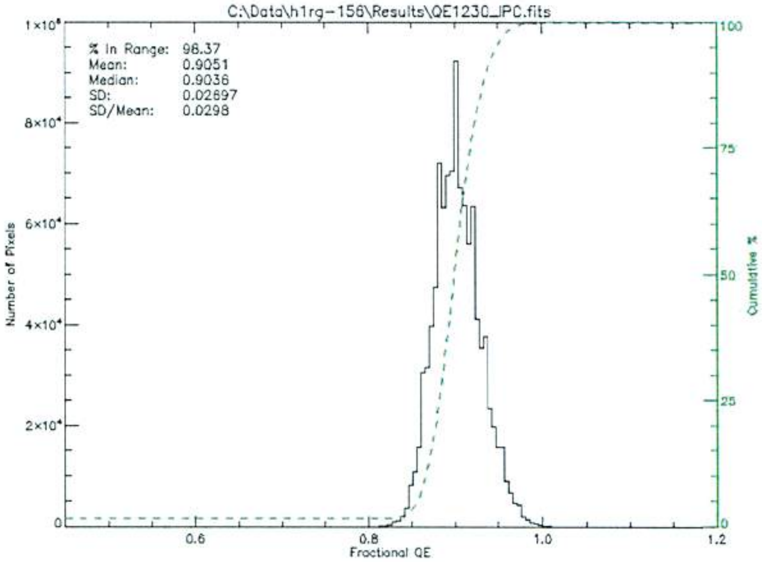




- 30 MHz polling clock, 0.1 ms integration time
- roll-over due to dead time
- at low flux, single detector slope is unity even with crosstalk
- at low flux, quad response is non-Poissonian with crosstalk

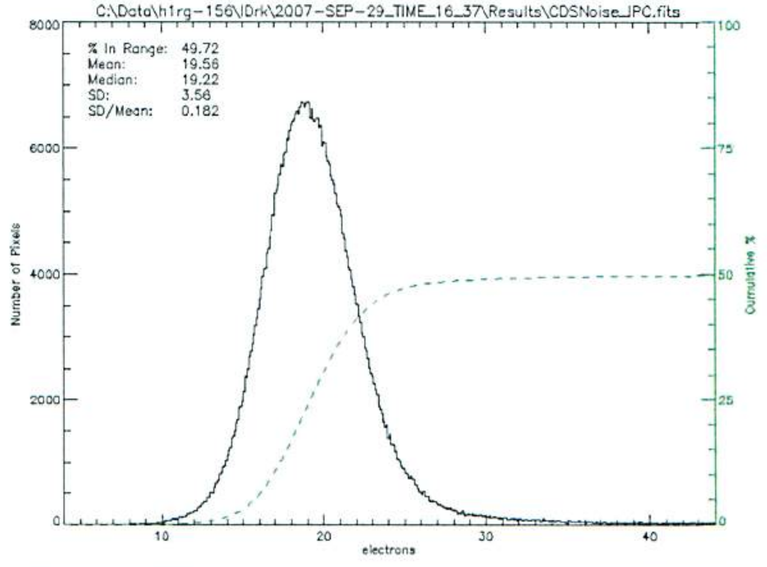
results courtesy of B. Aull

Mira QE at 1230 nm



Source: Teledyne_FPA_Performance_156_report.pdf

Mira Noise



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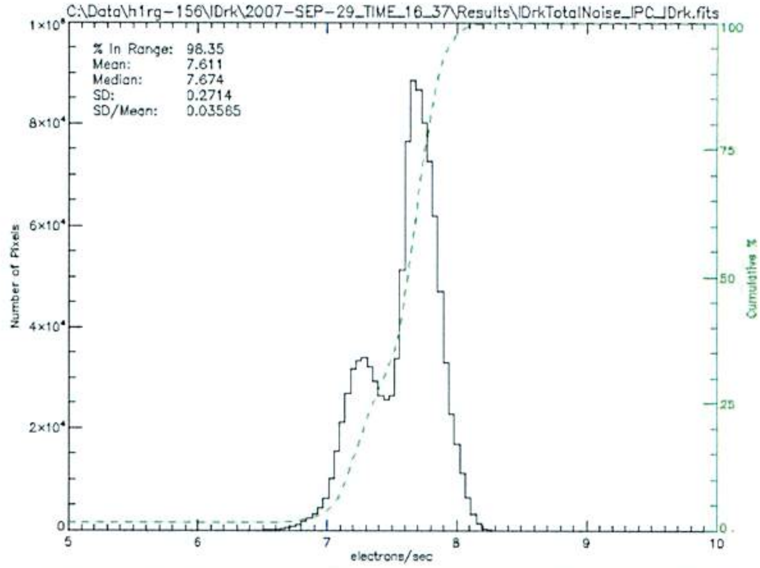
Mira Dark Current

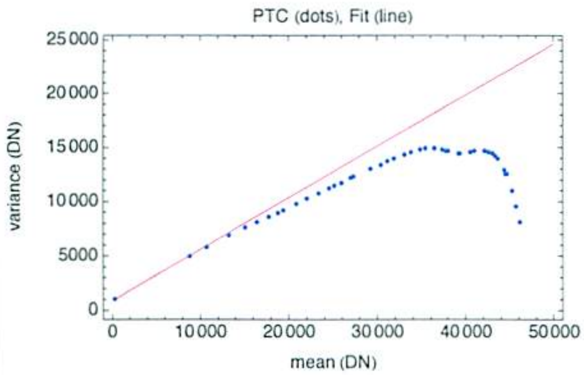


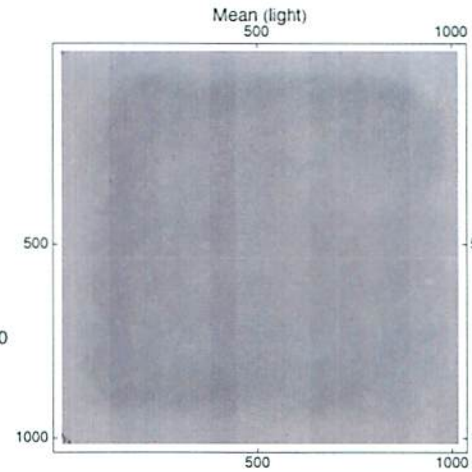
Source: Teledyne_FPA_Performance_156_report.pdf

Mira test parameters

- Measure
  - read noise, gain, well capacity (PTC)
  - dark current
  - quantum efficiency (1250, 1064, 1550 nm)
- Full frame, slow (low noise) readout
- Temperature controlled 85 kelvins

Mira PTC





Read noise ≈ 62 e–
Gain ≈ 2.1 e–/count
1016×1016 pixels
> 99 percent operable

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